

# **Results from an International Simulation Study on Coupled Thermal, Hydrological, and Mechanical (THM) Processes near Geological Nuclear Waste Repositories**

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## **INTRODUCTION**

This paper presents results from an international multiple-team simulation study on thermal, hydrological and mechanical (THM) interactions around underground waste emplacement drifts. The study is part of the ongoing DECOVALEX-THMC project described in detail by Birkholzer et al. (2005). The general goal of the project is to encourage multidisciplinary interactive and cooperative research on modeling coupled processes in geologic formations in support of the performance assessment for underground storage of radioactive waste. The main processes studied in the case of THM are heating of the rock mass with associated thermally induced strains and stresses and changes in hydrological rock properties. Two generic repository types with horizontal emplacement tunnels are considered within the project:

Type A) A high temperature (above boiling) repository in a deep unsaturated volcanic rock formation with emplacement in open gas-filled tunnels, similar to the Yucca Mountain Project concept

Type B) A low temperature (below boiling) repository in a deep saturated crystalline rock formation with emplacement in back-filled tunnels, a concept considered in many European countries and Japan.

The initial material properties for the two repository types are derived from measurements and previous DECOVALEX analyses of two major *in situ* experiments, representing data and processes occurring at the two repository types. The first one, representing Repository Type A, is the Yucca Mountain Drift Scale Test, conducted at Yucca Mountain, Nevada (Rutqvist et al., 2005). The second one, representing Repository Type B, is the FEBEX *In Situ* Test, conducted at the Grimsel Test Site, Switzerland (Alonso et al., 2005). Previous THM simulations of these two major field experiments have already demonstrated that the short-term (occurring over several years) coupled THM processes are well understood. In the present study, however, the models should be used to predict coupled THM processes over tens of thousands of years.

Four international teams from China, Germany, Japan, and USA are participating in this task (see Table 1). Altogether, five different numerical codes for coupled THM analysis are applied. DOE uses two alternative codes, TOUGH-FLAC (which is widely used within the Yucca Mountain Project) and ROCMAS. JNC uses a code named THAMES, BGR uses the GeoSys/Rockflow family of codes, and CAS works with the general purpose FEMLAB multi-physics software (see Table 1 for short description of each numerical simulator).

## **WORK DESCRIPTION**

Research teams participating in the research task are asked to conduct predictive analysis of the long-term coupled THM processes for the two repository types. The simulations are conducted on two-dimensional drift-scale models containing one horizontal emplacement tunnel, which for each repository type has different dimensions and thermal load (Figure 1). Participating research teams model the THM processes in the fractured rock close to the representative emplacement tunnel as a function of time, predict the changes in hydrological properties, and evaluate the impact on near-field flow processes. The simulations to be conducted include three phases:

Phase 1. Model inception

Phase 2. Preliminary model prediction and sensitivity analysis

Phase 3. Final model prediction with uncertainty range

The purpose of the model inception phase (Phase 1) is for the research teams to familiarize themselves with the problem by performing one simulation in which all the properties are explicitly provided. Thus in this phase no data or model uncertainties are considered, and changes in hydrological properties are neglected. The results of the research teams are compared even at this stage to assure that they are starting the problem on a common basis before further complexities are added in Phases 2 and 3. In Phase 2, the research teams are to develop their model and input material properties from available site data with the ultimate goal of predicting mechanically induced permanent changes. In Phase 3, the research teams are asked to make their final prediction, along with an evaluation of the uncertainties in their prediction.

## **RESULTS**

Currently (about one year into the three-year project), all teams have completed the necessary model development and have provided results for Phase 1 (model inception).

Figure 1 shows examples of temperature comparisons and stress-evolution comparisons obtained by the five different models for the two different repository types. The figure shows a generally good agreement for temperature and stress evolution, especially in the case of Repository Type A (Figure 1a). The more significant deviations in temperature evolution that can be seen for Point V1 for Repository Type B (Figure 1b) is explained by differences in the evolution of saturation-dependent thermal conductivity in the backfill. The observed disagreement in thermal stress by one model (dashed line in Figure 1c and d), is a result of a misconception of the initial stress and the in excavation modeling. One

the purposes of Phase 1 (model inception) is to eliminate such misconceptions and eliminate differences in the basic underlying thermal-mechanical calculations before moving on to Phase 2. Other results compared in Phase 1 include evolution of fluid pressure, saturation, displacement, and vertical flux.

## **CONCLUSIONS AND DISCUSSION**

In this paper, we present the progress of an international multiple-team study of coupled thermal, hydrological, and mechanical (THM) interactions associated with open and back-filled repository-drift designs in volcanic and crystalline rocks. A good agreement was achieved in calculated THM responses for both repository types, although some remaining deviations should be resolved in the near future. The main purpose of Phase 1 has been achieved—to make sure that the teams accurately calculate the basic thermal-mechanical responses and stress evolution, which are the driving forces for inducing permanent changes in hydrological properties. The research teams will then start with Phase 2, which is the preliminary model prediction and sensitivity analysis of permanent (irreversible) changes, and the impact of those changes on the fluid flow field around the emplacement drift.

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Table 1: Research teams and simulators applied within applied in this study

Research Team	Numerical simulator	Brief description of numerical simulator
<b>DOE</b>  U.S. Department of Energy's research team:  Lawrence Berkeley National Laboratory (LBNL)	<b>TOUGH-FLAC</b>	TOUGH-FLAC is a simulator for analysis of coupled THM processes under multi-phase fluid flow conditions developed at the LBNL in the last few years. The simulator is based on linking of the existing computer codes TOUGH2 and FLAC3D. It has been extensively used for analysis of coupled THM processes within the Yucca Mountain Project.
	<b>ROCMAS</b>	ROCMAS is a finite element program for analysis of coupled THM processes in porous and fractured rock developed at the LBNL since the late 1980s. In the late 1990s this code was extended to unsaturated media with single-phase liquid flow and vapor diffusion in a static gas phase. The code has been extensively applied in earlier phases of the DECOVALEX project for THM analysis in bentonite-rock systems.
<b>BGR</b>  Bundesanstalt für Geowissenschaften und Rohstoffe, Center for Applied Geosciences' research team:  University of Tübingen	<b>GeoSys/Rockflow</b>	GeoSys/Rockflow simulator is based on object oriented programming developed at the University of Tübingen in the last few years. It was first applied and the previous DECOVALEX phase for analysis of thermal-mechanical and thermal-hydrological processes and have recently been extended to THM analysis. For the present study an unsaturated single-phase liquid flow and vapor diffusion model is applied.
<b>CAS</b>  Chinese Academy of Sciences' research team	<b>FEMLAB</b>	CAS utilizes high level programming techniques within the framework the general finite element partial differential equation solver FEMLAB to solve coupled THM problems. The approach being developed for the present study includes unsaturated single-phase fluid flow and vapor diffusion model approach.
<b>JNC</b>  Japan Nuclear Cycle Development Institute's research team including Hazama Cooperation	<b>THAMES</b>	THAMES is a finite element program for analysis of coupled THM processes in porous and fractured rock developed at the Kyoto University since the late 1980s. The code has been extended to unsaturated media with single-phase liquid flow and vapor diffusion in a static gas phase. Like the ROCMAS code, the THAMES code has been extensively applied in earlier phases of the DECOVALEX project for THM analysis in bentonite-rock systems.

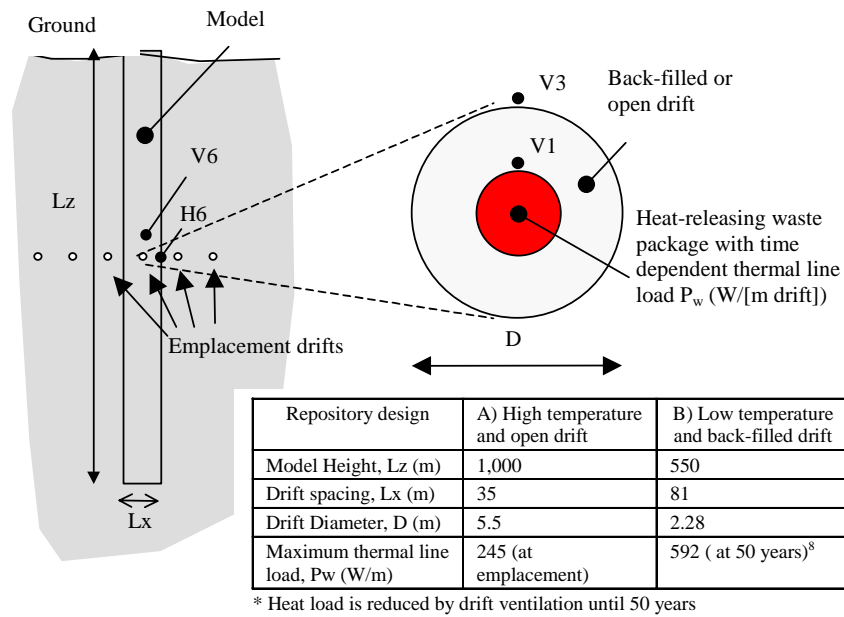
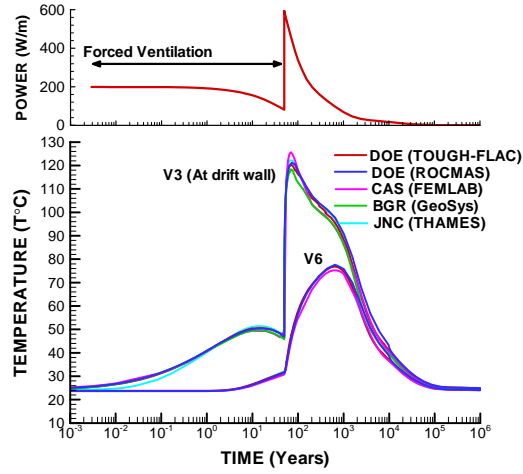
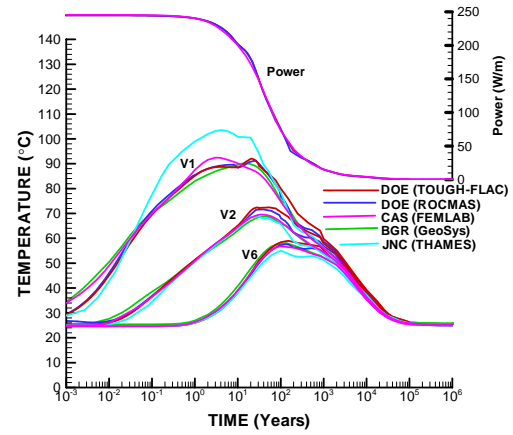


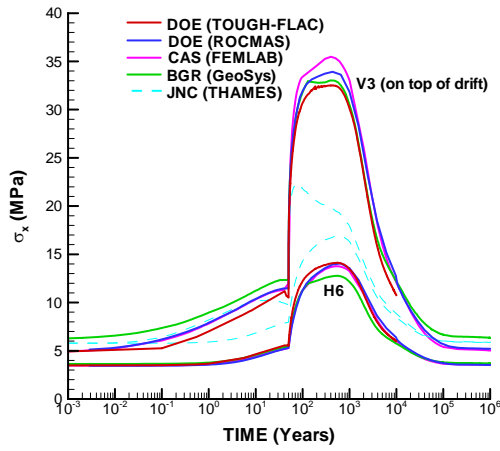
Figure 1. Two-dimensional model geometry for analysis of the two repository types (A and B) and location of some output points.



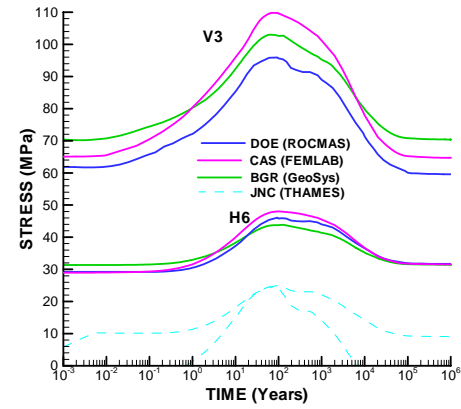
(a) Power and temperature evolution for Type A



(b) Power and temperature evolution for Type B



(d) Evolution of Horizontal stress for Type A



(d) Evolution of Horizontal stress for Type B

Figure 2. Evolution of thermal-mechanical responses for Repository Type A (high temperature open drift) and B (low temperature back-filled drift) repository. Approximate locations of Points V1, V3, V6, and H6 are given in Figure 1 and explanations of acronyms DOE, CAS, BGR and JNC are given in Table 1.